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Phytoremediation Pilot Study at Aberdeen Proving Ground, Maryland (Hirsh, 2002)

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Phytoremediation of Volatile Organic Compounds in Groundwater: Case Studies in Plume Control

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FOREWORD

The use of plants to remediate contaminated soil and groundwater constitutes an emerging technology that has generated a great deal of interest. EPA's Technology Innovation Office (TIO) provided a grant through the National Network for Environmental Management Studies (NNEMS) to assess the field performance of phytoremediation technologies to clean up volatile organic compounds in groundwater. This report was prepared by a graduate student from Virginia Polytechnic Institute and State University during the summer of 2002. It has been reproduced to help provide federal and state project managers responsible for hazardous waste sites with information on the current status of this technology.

This report provides a basic orientation and current status of phytoremediation for shallow groundwater. It contains information gathered from a range of currently available sources, including project documents, reports; periodicals, Internet searches, and personal communication with involved parties.

References for each case study are provided immediately following the case study. While sources are referenced as footnotes throughout the text, a comprehensive list of all documents (organized alphabetically) and individuals (listed by organization or company) that contributed to the writing of this report is available in the bibliography at the end of the report.

About the National Network for Environmental Management Studies (NNEMS)

NNEMS is a comprehensive fellowship program managed by the EPA's Office of Environmental Education. The purpose of the NNEMS Program is to provide students with practical research opportunities and experiences.

Each participating headquarters or regional office develops and sponsors projects for student research. The projects are narrow in scope to allow the student to complete the research by working full-time during the summer or part-time during the school year. Research fellowships are available in Environmental Policy, Regulations, and Law; Environmental Management and Administration; Environmental Science; Public Relations and Communications; and Computer Programming and Development.

NNEMS fellows receive a stipend at a level determined by the student's level of education, the duration of the research project, and the location of the research project. Fellowships are offered to undergraduate and graduate students. Students must meet certain eligibility criteria.

The report is available on the Internet at www.clu-in.org.

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Purpose

Trichloroethene (TCE) and tetrachloroethene (PCE) are the most prevalent groundwater contaminants in the United States.[1] This paper discusses how various plant species have been used to clean up these contaminants and other volatile organic compounds (VOCs) contaminating groundwater at several sites. In addition to a technology overview, this report provides insight into the field applications of phytoremediation, and discusses the technology performance as well as new developments and findings in this subject matter. The Appendices list information on 55 planned and ongoing phytoremediation projects addressing VOC-contaminated groundwater.

Laboratory studies have shown that phytoremediation of VOCs in groundwater has great potential. It is the purpose of this paper to summarize the status of this technology as applied to VOCs in the field. Following the Technology Overview, the focus of the report is a compilation of case studies implemented by scientists from a variety of organizations, government, academia, and the private sector.

Technology Overview

Phytoremediation is an emerging technology that involves the use of plants to remove organics and metals from soil and groundwater. Building upon plants' natural tendency to absorb organic and inorganic substances from the ground, phytoremediation uses a natural mechanism as an innovative technology for environmental remediation.

Phytoremediation of contaminated groundwater encompasses several mechanisms, which often occur simultaneously and lead to contaminant removal, degradation, or sequestration. Definitions of these terms tend to vary between sources; however, for the purposes of this report, descriptions of in situ phytoremediation mechanisms are as follows:

<u>Rhizofiltration</u>	The uptake of contaminants in water by absorption into plant roots
<u>Phytostabilization</u>	Usually refers to the immobilization of contaminants in the soil, but in some cases is also applied to water[2]
<u>Phytodegradation</u>	The degradation of organic contaminants within the plant
<u>Rhizodegradation</u>	The degradation of organic contaminants in the roots
<u>Transpiration</u>	Loss of water from the stomata of a plant leaf
<u>Diffusion</u>	The release of a contaminant through the plant stem/tree trunk

[1] Collins et al., 2002.

[2] Hauser et al., 1999.

Phytovolatilization The release of contaminants via transpiration and diffusion

As reflected in the above definitions, some plants are capable of more than water and contaminant uptake, and can also biodegrade, volatilize, and immobilize contaminants.

Due to its versatility, phytoremediation can easily be combined with other remediation efforts to maximize site clean-up results. Phytoremediation can complement more traditional methods for groundwater treatment, such as non-reactive barriers (slurry walls) and "pump-and-treat." This report will highlight the ability of phytoremediation to control groundwater movement hydraulically and to contain or capture a VOC contaminant plume, when used in conjunction with other technologies.

Hydraulic Control

Deep-rooted trees called phreatophytes are capable of reaching and removing large amounts of water from the ground through transpiration. Trees such as cottonwoods (poplars) or willows can transpire more than their total water content on a hot sunny day. Transpiration is influenced by plant density, leaf area index, radiant solar energy flux, depth to groundwater, temperature, relative humidity, and wind speed. Thus, depending on site conditions, the natural water consumption of trees can be exploited to influence and even control groundwater movement, resulting in contaminant plume capture.

Hydraulic influence can be evidenced by a decrease in water table elevation (even on a diurnal basis). Groundwater fluctuation can be measured by pressure transducers installed in wells located in the planted area. Groundwater use can also be monitored by indirect methods, such as transpiration estimates based on sap flow, leaf area, or meteorological data and contaminant mass reduction.[3] To demonstrate hydraulic containment of the contaminant plume, however, it is necessary to compare groundwater samples obtained in similar seasons from several years.[4]

Depending on the transmissivity of the aquifer (a function of its hydraulic conductivity and thickness), a cone of depression can form in the groundwater underneath an individual tree or under an entire plantation area.[5] This phenomenon was documented at the Aberdeen Proving Ground project, and resulted in a reversal of groundwater flow at that site during the summer months. On the other hand, in areas with clayey soils, groundwater uptake by trees may result in a mounding effect. Cones of depression can be difficult to identify if there is a topographic (and hydraulic) high point at the project site.

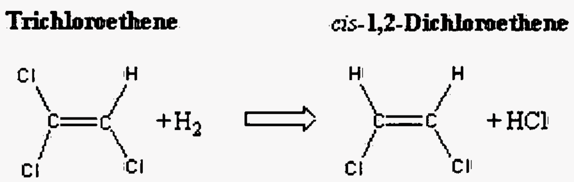
[3] Landmeyer, 2001.

[4] Ferro et al., 2002.

[5] Landmeyer, James. U. S. Geological Survey. Personal Communication, August 20, 2002.

Phytoremediation-Enhanced In Situ Bioremediation

A more active process than monitored natural attenuation, phytoremediation has also been used as a mechanism to augment natural degradative processes. Enhanced in situ bioremediation refers to the use of plants to increase the microbial population in the contaminated soil and groundwater by providing the necessary nutrients, moisture, and electron acceptors. Highly chlorinated VOCs (such as PCE and TCE) are best degraded anaerobically, while end products such as dichloroethene (DCE) and vinyl chloride are best dechlorinated aerobically. Through the production of root exudates as well as root decomposition, the presence of trees can promote a change in subsurface conditions from an aerobic to a mostly anaerobic state. Microorganisms then proceed to break down organic contaminants (such as TCE and its products) via reductive dechlorination. Reductive dechlorination of TCE to cis-1,2-DCE occurs by the following mechanism:



The complete degradation pathway for the process is:

$$\text{TCE} \rightarrow \text{cis-1,2-DCE} + \text{HCl} \rightarrow \text{vinyl chloride} + \text{HCl} \rightarrow \text{ethane} + \text{HCl}$$

Evidence of rhizodegradation via reductive dechlorination occurring in the soil and groundwater underneath the trees can be found by monitoring for increased microbial populations, lower dissolved oxygen concentrations, higher concentrations of reductive dechlorination breakdown products (DCE and vinyl chloride), and higher dissolved carbon concentrations. In addition, sulfide concentrations, methane production, ferrous/ferric iron ratio, and hydrogen gas generation can be indicators of low redox potentials, conducive to reductive dechlorination.

The Carswell Naval Air Station phytoremediation site has collected the types of data mentioned above since 1996. Results of phytoremediation-enhanced in situ bioremediation, as well as hydraulic control, at this site will be provided in the Field Studies section of this paper, and will also be evaluated in the Discussion at the end of the paper.

Modeling

Modeling programs such as MODFLOW are often used in the preliminary design stages of a phytoremediation project, and later after project implementation, to evaluate progress and optimize performance. Modeling programs have been effective in predicting contaminant removal rates as well as simulating the fate and transport of contaminant plumes and groundwater flow.

Groundwater flux can be estimated using Darcy's Law:

$$Q_a = K \cdot I \cdot A$$

where K = hydraulic conductivity (L/t)
I = hydraulic gradient (dimensionless)
A = cross-sectional area of the plume (L^2)

Two and three-dimensional capture zone calculations can also be used to characterize the plume geometrically. Based on this information, Analytical Element Method (AEM), numerical, and flow simulation models can be generated. Applications of these models will be discussed in greater detail in the field studies presented later in this paper.

Tree Selection and Planting Methods

Poplar and willow trees can be planted as whips, which are sections of one-year-old stems (about one inch in diameter and 18 inches long) harvested from branches during the dormant season.[6] "Poles" (non-rooted cuttings that are several feet longer than whips) or one to two-year-old transplanted trees (with bare, burlapped, or potted roots) may also be used. Larger, rooted trees tend to be more expensive than cuttings, but can be planted at sites where there is a need to see faster results.

Planting density also factors into the rate of contaminated groundwater removal. The amount of spacing between trees determines the time of leaf canopy closure, at which the transpiration rate of the trees (and thus contaminant removal) is maximized. Planting trees too close together for quicker canopy closure, however, can limit sunlight and inhibit tree growth. Because transpiration rates are factors of tree growth and canopy closure, project planning should include a tree configuration that maximizes the number of trees in an area at the same time as it maximizes the spacing between trees. Depending on the remediation timeframe, budget, and area available, closer or wider spaces may be selected.

In order to successfully remove contaminants from groundwater, tree roots must extend far enough to physically reach the contaminants. Hybrid poplars are phreatophytes that are commonly used in field studies for this reason. Not only does this species grow in a wide range of climates, its properties are also readily modified by cross-breeding. Other criteria that affect plant selection include soil type and contaminant type. Native tree species are often considered for phytoremediation projects because of their inherent site-suitability. Variety in tree species is desirable because it increases the plantation's chances of survival.

Soil moisture, soil temperature, density, and oxygen concentration can affect root growth. Various cultivation practices such as tilling can be used enhance root development. Tilling refers to the plowing of a field for the planting of rooted and non-rooted trees. Not only does the plowing aerate and loosen the soil, it also reduces the initial competition of the trees with weeds. Other methods of weed control include mulching and spraying with herbicide.

[6] Rock et al., 2002.

Depending on the depth to the saturated zone, soil type, tree type, and the project budget, the possible planting methods (in order of least to most expensive) include: dibble-bar planting, trenching, and augering. Dibble-bar planting refers to the use of a dibble-bar tool to plant 1.5 foot whips into hard soil. Planting by this method can be completed rather quickly at minimal expense, but trees may require irrigation for the first few years to ensure adequate access to water.[7]

Trenching is another planting method, where deep trenches are dug to create a preferential pathway for roots (Figure 1). Rooted trees or cuttings are then inserted, and the trench is backfilled with soft material (generally topsoil, compost, or peat).


Figure 1. Trenches at Carswell site (Rock, 2002)

In dry places, where the saturated zone is less than eight feet below the ground surface, boreholes can be drilled and 6 to 12 foot "poles" or bare-rooted stock can be inserted directly into the moist sediment. Boreholes can then be filled with a porous medium, leaving about a foot of the tree exposed above ground. Roots develop along the pole, leading to deep-rooted trees that often do not need to be irrigated.[8]

Augers also can be used to drill deeper holes into the ground (up to 40 feet), which can then be backfilled with sand (Figure 2). Poles are planted, leaving up to four feet above the surface. Disadvantages to drilling holes include its expense, as well as the longer length of time required for planting.

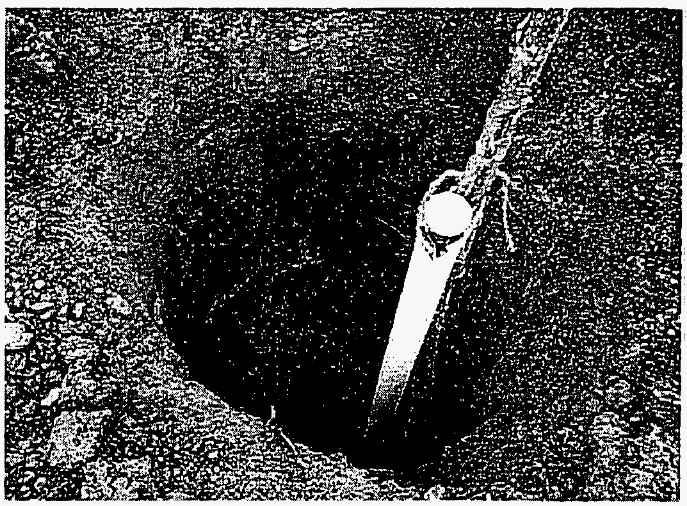


Figure 2. 10 ft hole augered through soil, rock, and concrete at Ashland site, 2000 (Photo courtesy of Ecolotree)

Monitoring

Periodic monitoring of a project over several years is necessary for purposes of comparison. Groundwater sampling at monitoring wells helps to determine if the contaminant plume is increasing, decreasing, or remaining the same.

[7] Rock, U. S. Environmental Protection Agency. Personal Communication, August 12, 2002.

[8] Ferro et al., 2002.

Assessing the effectiveness of phytoremediation often depends on indirect measures. In addition, the lag time between when a system is installed and when it is fully operational should be taken into account when evaluating the system. Full root development and canopy closure both may take several years to affect results.[9]

Figure 3 indicates several means of monitoring a phytoremediation system, once it is in place. Case studies described in the subsequent section will provide project results based on similar monitoring methods.

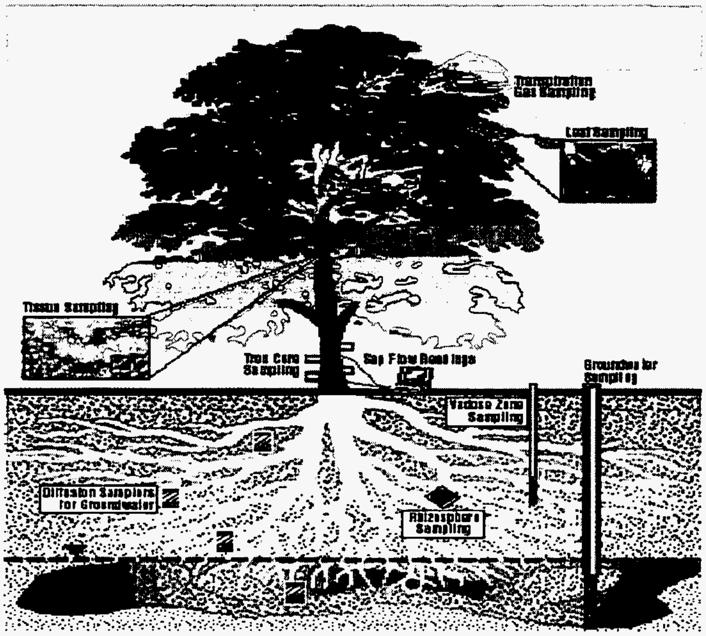


Figure 3. Phytoremediation system monitoring techniques (Hirsh, 2002)

Comprehensive Monitoring

- Transpiration Gas
- Transpiration Rate
- Tree Tissue
- Rhizosphere
- Microbial Activity
- Soil Conditions
- Weather
- Groundwater Hydrology

Benefits of Phytoremediation

One of the main advantages of phytoremediation is that it generally causes little environmental disturbance compared to traditional remediation methods. Vegetation used for phytostabilization prevents flooding and erosion, protects topsoil, and enhances ecosystem restoration efforts. Phytoremediation also tends to be a popular remediation technique because it produces an aesthetically pleasing site.

From an economic perspective, phytoremediation's appeal is due to its reputation as a low-cost technology, with system costs about 50-80 percent less than remedial alternatives.[10] For a comprehensive cost estimate of a phytoremediation project, the following factors must be taken into account:

[9] McLinn et al., 2001.

[10] USEPA, 2000.

Design costs
- Site characterization
- Work plan and report preparation
- Treatability and pilot testing

Installation costs
- Site preparation
  - Facilities removal
  - Debris removal
  - Utility line removal/relocation
- Soil preparation
  - Physical modification: tilling
  - Chelating Agents
  - pH control
  - Drainage
- Infrastructure
  - Irrigation System
  - Fencing
- Planting
  - Seeds, plants
  - Labor
  - Protection

Operating costs
- Maintenance
  - Irrigation water
  - Fertilizer
  - pH control
  - Chelating agent
  - Drainage water disposal
  - Pesticides
  - Fencing/pest control
  - Replanting
- Monitoring
  - Soil nutrients
  - Soil pH
  - Soil water
  - Plant nutrient status
  - Plant contaminant status
  - Tree sap flow monitoring
  - Air monitoring
  - Weather monitoring

(USEPA, 2000)

The domestic market for phytoremediation of organics in groundwater was valued at only $21 to $42 million this year. However, the market is projected to increase to $40 to $80 million by 2005.[11] Market projections reflect the common opinion that phytoremediation is a technology that is on the rise and will become more prevalent in the future.

Drawbacks of Phytoremediation

There are several limitations to phytoremediation. Because every hazardous waste site is unique, choosing the appropriate plant species to use can be difficult. Sites with multiple contaminants dissolved in groundwater may not be good candidates for phytoremediation, because while certain plants may be able to tolerate some contaminants, they may not be able to tolerate others. Also, the length of time required for contaminant removal can be a disadvantage to phytoremediation, as compared to other, more traditional cleanup technologies.[12]

Sites with high concentrations of contamination can also be too toxic for phytoremediation to be effective. Areas with widespread, low to medium level contamination are the best candidates for phytoremediation. Climatic factors such as temperature, amount of precipitation, and sunlight must also be taken into account in addition to important soil characteristics such as pH and water

[11] Glass, 1999.

[12] USEPA, 2000.

content.[13] Depth to groundwater may also be a limiting factor, since trees have been shown to be most effective at locations where the depth to groundwater does not exceed 12 feet.[14]

Selecting phytoremediation at a contaminated site may require more technical information than is usually available after a remedial investigation. Site-specific hydrogeological and contaminant transport data are not routinely collected.[15] This lack of data can lead to a poorly designed and poorly implemented project, which compromises the potential effectiveness of the plants and the site clean-up.

Lastly, the fate of contaminants after plant uptake is a subject that has to be addressed with further study. Low to no contaminants have been detected in air in or around phytoremediation sites, while larger fractions have been found in tree sap and tissue. Research thus far has not been able to definitively account for the fate of the entire contaminant mass estimated to have been removed from groundwater. A better grasp of how phytodegradation, transpiration, and diffusion processes affect the fate of contaminants would represent a major milestone in the acceptance of phytoremediation as a proven remediation technology.

Summary

As indicated in the above sections, phytoremediation projects are reliant upon a variety of factors, from tree survival to regular site monitoring, for their success. Because of the complexity of the technology, it is often difficult enough to assess the value of this innovative method of remediation at a single site, let alone prove the usefulness of this technology overall. The subsequent section presents descriptions of and results from several of the oldest phytoremediation projects in the United States, implemented between 1996 and 1998. It is hoped that this information will provide the appropriate private companies, government regulators, and university researchers with a better understanding of what is going on in the field today and what developments to look for in the future.

[13] USEPA, 2000.

[14] Eberts et al., 2003.

[15] Rock et al., 2002.

Selected Field Studies

Since the success of phytoremediation efforts tends to be very site-dependent, sharing information through case studies can be particularly helpful for professionals who are considering or are already implementing phytoremediation projects. The summaries included in this section include information on conditions at specific sites (contaminant concentrations, plume depth and dimensions), project implementation details (objectives, design), results to date, and references of available written material on the project.

Charts of all ongoing and anticipated phytoremediation projects that the author has identified (55 total) are also provided in the appendix of this report. These charts supply valuable reference information to other relevant studies, including a point of contact for each project.

The number of field studies that are currently being implemented has increased considerably since five years ago (see Appendix). Many of these projects have only been in operation for two to three years; therefore results are still too preliminary to discuss. Other projects, however, have now reached maturation, and researchers have a variety of data that they can use to evaluate the progress of phytoremediation at their sites. Some of these projects, such as the Aberdeen Proving Ground site in Maryland, the Carswell Naval Air Station site in Texas, and the Edward Sears Property site in New Jersey, have been designated by the North Atlantic Treaty Organization's Committee on Challenges of Modern Society (NATO/CCMS) as innovative remedial technology demonstration sites, and these (in addition to others) will be examined in detail below.

J-Field, Aberdeen Proving Ground, Edgewood, Maryland

SITE DESCRIPTION

The five-year field demonstration at J-Field, Aberdeen Proving Ground is one of the most extensively studied phytoremediation projects in the United States. The site consists of a one-acre area with 1,1,2,2-tetrachloroethane (1,1,2,2-TeCA) and trichloroethene (TCE) contaminated soil and groundwater. One hundred eighty three hybrid poplar trees (*P. deltoides x trichocarpa*) were planted in 1997, with the dual objective of containing the VOC plume and reducing contaminant mass through transformation and transpiration.

Trees were planted 10 feet apart, in a U-shaped configuration. At first, they were planted using plastic sleeves to promote downward root growth and groundwater uptake. After excavation and assessment, however, this method was found to restrict the lateral root growth necessary to prevent trees from blowing over during storm events and was thus abandoned in 1998. Boreholes were used with more satisfactory results during a later round of planting (2002), which added about 150 more hybrid poplars as well as 450 native trees (species such as tulip trees, silver maples, evergreen hollies, loblolly pines, oaks, and willows) to the site.

Conventional remediation technologies such as soil washing, soil vapor extraction, groundwater pump-and-treat, and groundwater circulation wells have been tested at J-Field, but the presence of unexploded ordnance, a low permeability aquifer, and the continuously-fed VOC plume have

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